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CARBON FOOTPRINTING

Uncertainties in the carbon footprint of refined wheat products: a case study on Swedish pasta

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Abstract
Purpose Calculating the carbon footprint (CF) of food is becoming increasingly important in climate change communication. To design effective CF labelling systems or reduction measures, it is necessary to understand the accuracy of the calculated CF values. This study quantified the uncertainty in the CF of wheat and of a common refined wheat-based product, pasta, for different resolutions of farm-level in-data to gain an increased understanding of the origins and magnitude of uncertainties in food CFs.
Methods A 'cradle-to-retail' CF study was performed on Swedish pasta and wheat cultivated in the region of Skåne on mineral soils. The uncertainty was quantified, using Monte Carlo simulation, for wheat from individual farms and for the mixture of wheat used for pasta production during a year, as well as for the pasta production process.
Results and discussion The mean pasta CF was 0.50 kg CO_2e/kg pasta (0.31 kg CO_2e/kg wheat before the milling process). The CF of wheat from one farm could not be determined more accurately than being in the range 0.22–0.56 kg CO_2e/kg wheat, even though all farm-level primary data were collected. The wheat mixture CF varied much less, approximately ±10–20% from the mean (95% certainty) for different years. Reducing farm-level data collection to only the most influential parameters—yield, amount of N and regional soil conditions—increased the uncertainty range by between 6% and 19% for different years for the wheat mixture. The dominant uncertainty was in N_2O emissions from soil, which was also the process that contributed most to the CF.
Conclusions The variation in the wheat mix CF uncertainty range was greater between years, due to different numbers of farms being included for the different years, than between collecting all farm-level primary data or only the most influential parameters. More precise methods for assessing soil N_2O emissions are needed to decrease the uncertainty significantly.
Recommendations Due to the difficulties in calculating accurate values, finding other ways of differentiating between producers than calculating numerical CFs might be more fruitful and fair. When legislation requires numerical CF values, CF practitioners have little option but to continue using existing methods and data collection strategies. However, they can provide input on improvement, contribute to standardisation processes and help raise awareness and knowledge of the associated uncertainty in the data through studies like this one.

Keywords Carbon footprint · Carbon labelling · Food products · Pasta · Uncertainty analysis · Wheat products

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1 Background, aim and scope

Wheat is the second most cultivated agricultural product on the globe after rice (FAO 2009). In Sweden, wheat is the third most common crop on arable land after temporary grasses and barley (SCB 2009). A small proportion of Swedish wheat is used for ethanol production, whilst the rest is used either as animal feed or for direct human consumption in the form of bread, breakfast cereals, pasta, table wheat, etc. Pasta is a product that has grown steadily in popularity in Sweden, with per capita consumption having more than doubled since 1990, reaching 9.5 kg in 2006 (SCB 2009).

Since wheat is one of the most important agricultural products, the environmental aspects of Swedish wheat cultivation have been analysed in a number of studies, the most recent by Bernesson (2004), Cederberg et al. (2005), Tidåker et al. (2005), Flysjö et al. (2008) and Ahlgren et al. (2009). Lately, due to the increased focus on global warming, the carbon footprint (CF) of food products has become increasingly important (Weidema et al. 2008). The CF is a measurement of the amount of greenhouse gases (GHG) emitted during the life cycle of a product and is the same as the global warming potential. The farm gate CF values reported in the studies cited above vary between 0.25 and 0.47 kg CO_2e/kg wheat. Methodological choices differ between the studies and explain some of the differences in the results. A great source of variability is the intrinsic and 'unavoidable' variations due to natural conditions that lie outside the control of the producer, such as differences in yield due to geographical location. Controllable factors such as differences in fertilisation strategy and energy sources also contribute to the variation. In addition, the results are associated with uncertainty from the methods used to calculate the CF, above all in the models for calculating GHG emissions from cultivated soils (increased N_2O emissions due to nitrification and denitrification and CO_2 emissions due to soil disturbance). In order to efficiently act on and use the CF value of a food product, the sources and magnitude of the uncertainty in the data must be understood.

Röös et al. (2010) quantified the uncertainty in the CF of a common food product, table potatoes. When geographical region and potato variety were fixed, the CF still varied between −17% and +30% from the mean between farms and years. Compared with potatoes, a product often sold directly to the supermarket, tracing the emissions from pasta production is complicated by the fact that the main ingredient, wheat, is usually transported to a few large mills and mixed with wheat from other wheat producers, not uncommonly in several steps. For food safety reasons, European legislation forces food producers to set up systems for tracing the origin of all ingredients, which in theory would make it possible to trace batches of wheat back to an individual farm (European Parliament 2002). However, the data necessary to calculate the CF of the wheat mixture, such as yield, fertiliser and energy types and amounts, are not being collected from the wheat producers. Introducing such reporting from farmers would make it possible to calculate more accurate CFs, but the value would still have a degree of uncertainty due to the uncertainty in the models used to calculate the CF, the measuring uncertainty for the farm-level parameters and the uncertainty in emissions caused by production and transport of the inputs used during cultivation. Interesting questions that arise include how precise the CF would be if careful data collection were performed down to farm level and whether collecting data on only the most influential parameters in order to have a CF calculation system that is easier to manage and control would affect the precision in the CF.

The reasons for calculating CF values for food are several. One is to enable differentiation between wheat producers, for example to economically reward production with low GHG emissions. It is not improbable that low CF values on food can become an important means of competition, leading to food producers demanding wheat produced with low GHG emissions from their wheat suppliers. For European ethanol production, this is already a reality with the introduction of the sustainability criteria for biofuels, which require that the use of biofuels must lead to a reduction in GHG emissions of 35% compared with fossil fuels (European Parliament 2009). This in turn places demands on the GHG emissions allowed from the cultivation of biomass used for ethanol production, wheat being the most important ethanol crop in Sweden. This use of the CF value would require data collection on farm level.

Another purpose of calculating the CF of food could be to guide environmentally conscious consumers in their quest for the most climate-friendly food, e.g. by some type of carbon label on the food packaging. Different forms of CF labelling of food products, each with their pros and cons, are appearing on the market (Olofdotter and Juul 2008; Röös and Tjärnemo 2011). France has legislated that starting from 2011, all products on the French market, including food products, must contain information on their climate impact. It has not yet been decided exactly how the information should be calculated and displayed, but several voluntary labelling initiatives already exist in France, displaying numerical information using several sets of units (Ministère de l'Ecologie 2010). However, questions remain regarding the confidence with which such numbers can actually be expressed for common food products.

The purpose of this study was to quantify the uncertainty in the CF of wheat and a common refined wheat-based product, pasta, for different resolutions of the farm-level in-data in order to gain an increased understanding of the origins and magnitude of the uncertainties in food product CFs. Specific objectives were to quantify how different levels of traceability in the parameters affected the precision in the CF and to examine the importance of different parameters in the calculation of the CF and their contribution to the uncertainty. Assuming that food producers are setting requirements on 'low-emitting wheat', the confidence in a comparison between wheat causing lower emissions of GHG was also quantified.

Kungsörnens Gammeldags Idealmakaroner (KGI), a common Swedish pasta variety, was chosen as an example of a wheat-based food product. KGI is prepared in the Lantmännen pasta plant in Järna from 100% Swedish flour produced at the Lantmännen mill in Malmö, in the Skåne region of southern Sweden. The results from this case study were then used to discuss difficulties in the calculation of

food product CFs and the consequences of these challenges when using food product CFs for different purposes.

2 Materials and methods

2.1 System boundaries, functional unit and allocations

The study was carried out as a 'cradle-to-retail' life cycle assessment (LCA) study with climate impact as the only impact category, hence resulting in a CF study. The functional unit was 1 kg of KGI in paper packaging available for sale in a supermarket in Stockholm. The calculations were divided into two parts: (1) primary production of wheat and (2) processing from wheat to pasta. In part 1, emissions arising from all on-farm activities related to the wheat cultivation were included, as well as production and transport of all inputs such as fertilisers and fuels, and production, maintenance and waste handling of machinery and buildings. Transport from farm to mill was also included in part 1. In part 2, milling of the wheat to flour, transport of the wheat from the mill in Skåne to the pasta plant in Järna (railway) and pasta baking at the pasta plant were included, as was production of the packaging material, the packaging process and distribution from the pasta plant to the supermarket in Stockholm. Several results are also presented separately for the functional unit 1 kg of wheat before the milling process (part 1).

With few exceptions, the mill in Malmö collects wheat from Skåne, a region that produces close to 30% of Swedish wheat (SCB 2009). In Skåne, 1.5% of wheat cultivation is carried out on organic soils (Berglund et al. 2009), which are known to cause exceptionally high emissions of N_2O and CO_2 (IPCC 2006). However, cultivation on organic soils was not included here as such cultivation would always result in a CF several times higher than that for cultivation on mineral soils (Ahlgren et al. 2009) and as it is probable that wheat from organic soils would be treated as an exception when considering low emitting production. For example, in the Swedish climate certification programme for food, cultivation of annual crops is not allowed on organic soils at all (CCfF 2010). The straw from wheat production was assumed to be left on the field, and hence all emissions from wheat production were allocated to the wheat grain.[1] Emissions from storage and production of organic fertilisers (manure) were allocated to the animal production system, and the production of the organic fertilisers was 'free' of environmental burden in this study. Economic allocation should be avoided if possible in LCA (ISO 2006a, b). However, economic allocation was nevertheless used in this study to divide the GHG emissions between the three products produced in the milling of the wheat to flour: flour, wheat bran and wheat flour for animal feed. This was because the focus of this study was on uncertainty in in-data and in the methods used to quantify emissions at the farm level and not the uncertainty arising from methodological choices (for different types of uncertainty in LCA, see Björklund (2002)). As a result of the economic allocation, 92% of the GHG emissions from wheat cultivation and wheat transport from the farm to the mill were allocated to the flour used for pasta baking. The amount of wheat needed for the production of 1 kg KGI was 1.18 kg. The amount of seed needed in the cultivation of wheat was subtracted from the wheat yield. The biogenic uptake of CO_2 during wheat cultivation and the subsequent release during digestion was not included, although this can be seen as a violation of the standardised LCA methodology (ISO 2006a, b). It has become common practice not to include this uptake in food CF calculations, one reason being the confusion caused by negative CF numbers. A more detailed description of the system can be found in Röös (2010).

2.2 Analytical methods

Methodological choices and choices regarding which data to use, data gaps and temporal and spatial variations in data, measuring uncertainty and mistakes are all sources of uncertainty in life cycle assessment (Björklund 2002; Heijungs and Huijbregts 2004). This study focused on data variability and uncertainty and, to some extent, model uncertainty in the methods used to quantify the emissions at farm level. However, model and data uncertainty cannot be clearly divided (Koning et al. 2010). For example, the data from aggregated background processes, e.g. electricity production, contain both data and model uncertainty.

In part 1 (wheat production), a number of scenarios (summarised in Table 1) were designed to study, using Monte Carlo (MC) simulation (Rubinstein and Kroese 2007), how precision in the farm-level primary data affected the resulting wheat CF. The same uncertainty and variation for secondary data/emission factors (EF) were used for all scenarios (Table 2) as more careful collection of data for these background processes (production of pesticides, fertilisers, electricity, etc.) is not currently feasible in a realistic CF calculation situation since these products are not currently CF-declared. The uncertainty in the primary data/activity data, which was set to represent the measuring uncertainty in a real-life farm-level data collection process, was also kept constant in all scenarios. The uncertainty in

[1] This is a realistic assumption since all data are from pure crop-producing farms (and no animal-producing farms, which would collect straw for bedding purposes for example). However, this will probably change as future increased straw prices will stimulate farmers to collect the straw and sell it to the market.

Table 1 Wheat CF calculation scenarios

Scenario	Description	Farm-level primary data used in the simulations (yield and amounts of fertilisers, mineral and/or organic, known in all scenarios)	Results show
1a	'Advanced traceability—one farm' One typical farm in Skåne during one year (2007)	Only measuring uncertainty included, since all farm data assumed to be collected from the farms (fuel, fertilisers, machinery, electricity and pesticides)	Best CF precision possible with currently available CF calculation methods and realistic farm level data collection methods from one farm
1b	'Basic traceability—one farm' One typical farm in Skåne during one year (2007)	Measuring uncertainty and variation included. The variation described by realistic values in Skåne	Precision in the CF when only data on yield, amount and type of N fertiliser and municipality are collected from the farm
2a	Advanced traceability—several farms' Farms in Skåne delivering to the Malmö mill during one year Individual calculations for the years 2001, 2003, 2005 and 2007	One random value[a] for the Skåne region used for primary data with only measuring uncertainty, since all farm data assumed to be known (fuel, fertilisers, machinery, electricity and pesticides)	Precision in the CF of a yearly mixture of wheat and wheat CF from individual farms assuming collection of primary data for all individual farms
2b	'Basic traceability—several farms' Farms in Skåne delivering to the Malmö mill during one year Individual calculations for the years 2001, 2003, 2005 and 2007	Measuring uncertainty and variation included. The variation described by realistic values in Skåne	Precision in the CF of a yearly mixture of wheat and wheat CF from individual farms when only data on yield, amount and type of N fertiliser and municipality are collected from the farms

[a] From the distributions describing a parameter (see Table 3), one random value was drawn for each farm

the N_2O emissions from soils proved to be very dominant, so all simulations were also performed without uncertainty from N_2O emissions from soils in order to make the uncertainty contribution from other parameters clearer.

In scenarios 1a and 1b, primary data from only one typical farm for the year 2007 were used, giving a measurement of the precision in the currently available CF calculation methods. In addition to the MC simulation uncertainty analysis, an uncertainty importance analysis (Björklund 2002) for the typical farm used in scenarios 1a and 1b was performed. Realistic boundary values were used to determine how individual parameters contributed to the end-result CF. A mean value was also calculated using the mean values for all in-data.

Scenarios 2a and 2b took into account the fact that during a year, wheat-based products are produced from wheat originating from several different farms. The CF of the mix of wheat from one year was calculated, as well as the CF from individual farms during a certain year. In scenarios 1a and 2a, it was assumed that all primary data (Table 3) could be traced and collected from the farm, a process referred to as 'advanced traceability'. Scenarios 1b and 2b described a case of 'basic traceability' in which the data collection process was simplified to only include yield, the amounts of N fertilisers (mineral and organic) and the municipality in which the farm is located (used for determining the typical soil humus content). These parameters were chosen since they proved to be the most influential in the uncertainty importance analysis and since they are already recorded on the farm, so they would be easy to collect. The CFs for scenarios 2a and 2b were calculated separately for the years 2001, 2003, 2005 and 2007.

By pairwise comparisons of the wheat mix CF from a group of 'low-emitting wheat producers' and the wheat mix CF from 'all wheat producers included in this study' (outcome of the MC simulations using the basic traceability), the probability that the wheat CF mix from the 'low-emitting' farms was actually lower than the wheat mix CF from all of the farms was estimated, i.e. the confidence level in the comparison. The purpose of such a comparison was to investigate the confidence with which a producer could claim to have 'low-emitting wheat-based products' by selecting wheat from the farms with the lowest emissions compared with using wheat from all the farms. The groups were formed based on mean wheat CFs for the farms, calculated using the mean values without uncertainty or variation. Twenty per cent of the farms, sorted in ascending order by mean wheat CF for a specific farm, for each year, were put in the low-emitting group.

Part 2 of the KGI production process (processing wheat into pasta) differed from part 1 as the processes included were the same for all scenarios (no variation) and correlated for all farms since processing is carried out at the same mill and pasta plant. However, the in-data for calculating the CF

Table 2 Emission factors for the production and transport of inputs and transport: uncertainty contains both variation and measurement uncertainty expressed as the geometric standard deviation for lognormal distribution (approximate percentage value corresponding to 95% confidence interval in parentheses)

	Mean	Uncertainty
N fertilisers[a]	6.8 kg CO_2e/kg N	1.15 (±30%)
P fertilisers[a]	0.4 kg CO_2e/kg P	1.15 (±30%)
K fertilisers[a]	0.3 kg CO_2e/kg K	1.15 (±30%)
Pesticides[b]	5.4 kg CO_2e/kg active substance	1.15 (±30%)
Diesel[c]	0.004 kg CO_2e/MJ	1.02 (±4%)
Cardboard[d]	0.24 kg CO_2e/kg board	1.05 (±10%)
Corrugated board[d]	0.54 kg CO_2e/kg board	1.05 (±10%)
Plastic film[d]	1.9 kg CO_2e/kg film	1.05 (±10%)
Electricity[e]	0.024 kg CO_2e/MJ	1.20 (±35%)
Natural gas[f]	0.072 kg CO_2e/MJ	1.08 (±15%)
Distinct heating[d]	0.058 kg CO_2e/MJ	1.05 (±10%)
Biofuel[d]	0.004 kg CO_2e/MJ	1.05 (±10%)
Agri. machinery[f]	3.8–5.8 kg CO_2e/kg machinery	1.06 (±12%)
Agri. buildings[f]	186 kg CO_2e/m^2	1.06 (±12%)
Road transport[g]	0.068 kg CO_2e/ton-km	1.09 (±17%)
Railway transport[g]	0.000068 kg CO_2e/ton-km	1.01 (±2%)
Sea transport[g]	0.022 kg CO_2e/ton-km	1.09 (±17%)

[a] From Jenssen and Kongshaug (2003)

[b] From Kaltschmitt and Reinhardt (1997)

[c] From Uppenberg et al. (2001)

[d] From Sofie Karlsson, Project manager, Lantmännen R&D, Stockholm, Sweden, personal communication

[e] Nordic electricity mix: from Nordel (2005)

[f] From ecoinvent Centre (2007)

[g] Swedish electricity mix for railway (due to the minor importance of this process, it was not recalculated using Nordic electricity mix): from NTM Calc (2010)

for this part are associated with measuring uncertainty, and a separate MC simulation was performed to quantify the uncertainty from this part of the process.

When performing MC simulation, it is necessary to consider dependencies between parameters as failing to take correlations into account will lead to the uncertainty being overestimated (Björklund 2002). Determining parameter relationships is complicated for farming systems due to the large variability in natural systems and the many interconnected parameters involved (Payraudeau et al. 2007). One important correlation is that between yield and the amount of fertiliser used since both are sensitive parameters in the CF calculation of food products (see, e.g. Ahlgren et al. 2009; Röös et al. 2010). In general, increased amounts of fertiliser give higher yields, but several other parameters also determine the yield, such as soil quality, weather conditions and pest attacks, making it difficult to establish a relationship between fertiliser amounts and yield that is usable in MC simulations. In this study, this difficulty was avoided by using actual yield levels and fertiliser amounts for the specific farms collected by the national statistics agency. Fuel consumption was correlated to soil clay content since heavier soils require more fuel during tillage operations. For a complete explanation of all parameters and their correlation to each other, see Röös (2010).

Dependencies between farms could also influence the uncertainty. For example, if mineral fertilisers from the same producer are used on the farms being compared, the uncertainty in the comparison will be reduced. However, such inter-farm dependencies were not accounted for in this study, which means that the confidence in the comparison between the low-emitting farms and the rest of the farms was somewhat underestimated.

2.3 Data collection

The primary data used in the study are summarised in Table 3. Parameters that were traced to farm level in scenarios 2a and 2b are described by both a variation that outlines the variability between farms in the region and years, and an uncertainty distribution that describes the precision with which these can be collected in current farming practice without introducing any additional measuring equipment or routines, i.e. measuring uncertainty. The distribution of variation and uncertainty for primary data was estimated qualitatively based on existing data and expert knowledge of the process. For yield levels and fertiliser amounts, only measuring uncertainty was included since these data were assumed to be collected directly from the farms in all scenarios. Although the amounts of pesticides and seed used vary, as does the number of buildings to maintain on the farm, these variations were not included since it has been shown in numerous studies that these parameters have little influence on the final CF value (see, e.g. Ahlgren et al. 2009; Röös et al. 2010).

Wheat yield data are collected every year by the Swedish national statistics agency, Statistics Sweden (SCB), from a number of selected farms throughout Sweden (SCB 2010). Fertiliser amounts and types are collected every second year (in odd years) from another selection of farms (SCB 2008a). Some farms are present in both surveys in the same year, making correlated yields and fertiliser amounts available from these farms for some years. The farms that appeared in both the yield and fertiliser surveys during odd years were chosen to represent the farms that deliver wheat to the Lantmännen Malmö mill. The farms included in the study were hence not the true farms that delivered wheat to the Malmö mill, but make a good representation of the farms likely to have delivered to the Malmö mill since wheat is collected by the Malmö mill from varying farms throughout

Table 3 Primary data/activity data on KGI production

	Mean values (2007)	Variation	Uncertainty applied in all scenarios, geometric standard deviation of a lognormal distribution (approximate percentage value corresponding to 95% confidence interval in parentheses)
Part 1: Wheat cultivation			
Clay content[a]	14%	Distribution from measurements in the corresponding municipality	
Humus content[a]	3.4%		
Yield[b]	7470 kg/ha	Values from each specific farm	1.01 (±2%)
Moisture content at harvest[c]	16.1%	Lognormal distribution, geometric SD: 1.02	1.01 (±2%)
Fuel tillage operations[d]	69 l diesel/ha	Mix[j]	1.16 (±30%)
Amount of N fertiliser[b]	175 kg/ha	Values from each specific farm	1.05 (±10%)
Amount of P fertiliser[b]	16 kg/ha	In scenarios 1a and 2a—values from each specific farm	1.05 (±10%)
Amount of K fertiliser[b]	26 kg/ha	In scenarios 1b and 2b—lognormal distribution, geometric SD: 1.50	1.05 (±10%)
Amount of seed[e]	180 kg/ha	Not included	1.01 (±2%)
Pesticides[f]	1.2 kg/ha	Not included	1.01 (±2%)
Amount of farm machinery[g]	22 kg/ha year	Mix[k]	1.05 (±10%)
Amount of farm buildings[g]	0.040 m^2/ha year	Not included	1.05 (±10%)
Energy used for wheat drying	5.8 MJ oil/kg water	Lognormal distribution, geometric SD: 1.06	1.01 (±2%)
	300 MJ electricity/ha	Lognormal distribution, geometric SD: 1.05	
Distance farm to mill[h]	50 km	Uniform distribution, 5–95 km	1.035 (±7%)
Part 2: Processing from wheat to pasta			
Energy used in mill and pasta plant[i]	Confidential	Negligible (same mill and plant)	1.025 (±5%)
Distance mill to pasta plant[h]	600 km	Negligible	Negligible (railway)
Amount of cardboard paper[i]	66 g/kg pasta	Negligible	1.0025 (±0.5%)
Amount of corrugated board[i]	28 g/kg pasta	Negligible	1.0025 (±0.5%)
Amount of plastic film[i]	1.1 g/kg pasta	Negligible	1.0025 (±0.5%)
Distribution distance[h]	50 km	Not included	1.035 (±7%)

The variation (third column) outlines the intrinsic variability between farms and years. The uncertainty (fourth column) describes the precision with which the parameters can be collected in current farming practice without introducing any additional measuring equipment or routines, i.e. measuring uncertainty

[a] From SLU Mark (2010)

[b] From Statistics Sweden (farm-level detailed data prepared especially for this study)

[c] From SLU Fältforsk (2010)

[d] From Lindgren et al. (2002) and Mattsson et al. (2001)

[e] From Ahlgren et al. (2009)

[f] From SCB (2008b)

[g] From ecoinvent Centre (2007)

[h] From Eniro (2010)

[i] From Sofie Karlsson, Project manager, Lantmännen R&D, Stockholm, Sweden, personal communication

[j] The distribution for fuel consumption variation is a mixture of a discrete distribution of the number of repetitions for different operations and a lognormal distribution describing variation due to driving styles and the combination of tractor and equipment

[k] The distribution for the variation in the amount of machinery is a mixture of relationships and distributions describing variation due to the soil clay content, weight and lifetime differences

the region of Skåne based on quality requirements and price, and no other selection criteria. The proportions of wheat delivered from different farms were based on the total yields from the farms, hence assuming that all wheat from the selected farms was delivered to the mill in Malmö. To minimise the inclusion of feed wheat, only farms without animals were included.

The national statistics on yield and fertiliser use include information on the municipality in which the farms are located, and municipality-level statistics on the humus and clay content in soil were taken from the Swedish soil and crop inventory (SLU Mark 2010). The moisture content at harvest (used to calculate the amount of water that needs to be dried off) was collected from

SLU Växtforsk (2010). Data from the processing step in terms of energy use in the Malmö mill and in the Järna pasta plant and the amount of packaging material were obtained directly from the actual sites and deemed as having good precision and no variation between years (Sofie Karlsson, Project manager, Lantmännen R&D, Stockholm, Sweden, personal communication).

Secondary data/emission factors were collected from literature data, as would be the case in a practical CF system, as long as, e.g. the inputs, transport, etc. themselves are not carbon footprint-declared. For EFs, variation (due to, e.g. different production technology) and measurement uncertainty were grouped into one uncertainty distribution, and the methodology based on quality indicators (Weidema and Wesnaes 1996; Frischknecht et al. 2004) was used to assess the uncertainty. IPCC methodology (IPCC 2006) was used to calculate N_2O emissions from arable soil, whilst CO_2 emission or sequestration due to changes in the soil carbon pool was calculated using the ICBM model (Andrén et al. 2004). The EFs, including sources, are summarised in Table 2 and explained in more detail in Röös (2010).

3 Results

3.1 Uncertainty in contributing processes and individual parameters

The mean CF of 1 kg of KGI when assuming that the wheat came from one representative farm in the Skåne region in the year 2007 (calculated using the mean values in Table 3) was 0.50 kg CO_2e/kg (0.31 kg CO_2e/kg wheat before the milling process). The main contributing processes are shown in Fig. 1. The error bars show the uncertainty as a 2.5–97.5 percentile range in each individual process. The N_2O emissions from soil, the production of mineral fertilisers and the processing of the pasta were the processes that contributed most to the CF. The N_2O emissions from soil and the production of mineral fertilisers were also the processes associated with the greatest uncertainty. The uncertainty importance analysis (Table 4) revealed that the EFs for N_2O greatly influenced the CF end-result. Realistic variations in the amount of N fertiliser, the yield and the soil humus content also affected the CF greatly.

3.2 Uncertainty analysis

The outcomes from the uncertainty analysis of part 1 (wheat production) are summarised in Table 5. When the MC simulation was performed for one farm, 95% of the wheat CF values fell between 0.22 and 0.56 kg CO_2e/kg wheat when all farm-level primary data were assumed to be collected (scenario 1a). The boundaries were only slightly affected (0.22–0.57 kg CO_2e/kg wheat) when the data collection was restricted to the parameters yield, amount of mineral and organic N fertiliser and regional soil conditions (scenario 1b), giving a difference in range between scenarios 1a and 1b of only 3%. When uncertainty from N_2O emissions from soils was excluded, the range decreased considerably to approximately one third that of the advanced traceability scenario (0.26–0.37 kg CO_2e/kg wheat), and less careful data collection (basic traceability) then turned out to increase the range by 40%. Hence, the large uncertainty in soil N_2O emissions masks variations and uncertainties in other parameters.

Simulating several farms, as in scenarios 2a and 2b, revealed that the variation in CF between farms was large (see Table 5 and Fig. 2). For example, for the year 2005, wheat CF values varied between 0.18 and 0.58 kg CO_2e/kg wheat (see ‘Farms’ column in Table 5). A producer of wheat-based products would use wheat from several farms during a year, so a CF value of the mix of wheat that was delivered to

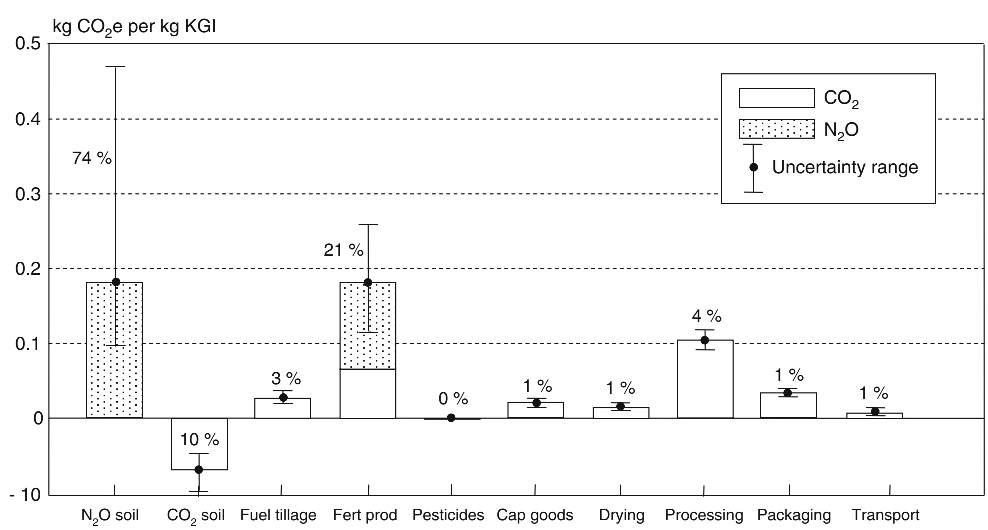


Fig. 1 Contributing processes to the KGI CF in scenario 1a. *Error bars* show uncertainty as the range between the 2.5 and 97.5 percentiles. Numbers are the relative contribution to uncertainty from an individual process as the range divided by the total mean CF

Table 4 Uncertainty importance analysis

	Boundary values		Change in wheat CF (%)[a]	
Humus content (%)	2.4	11	−3	+23
Yield (kg/ha)	3,700	11,000	+37	−20
Amount of N (kg/ha)	49	357	−38	+7
EF production of mineral fertilisers (kg CO_2e/kg N)	5.2	9.0	−7	+9
EF N_2O from mineral fertilisers (kg N2O–N/kg applied N)	0.003	0.03	−14	+41
EF N_2O crop residuals (kg N2O–N/kg applied N)	0.003	0.03	−4	+11
EF N_2O leakage (kg N2O–N/kg applied N)	0.0005	0.025	−2	+5

Parameters that showed an importance to the KGI CF of more than 5%. Data from farms in the region of Skåne included in the study during years 2001, 2003, 2005 and 2007

[a] Change relative to mean wheat CF value (0.31 kg CO_2e/kg wheat) calculated using mean values in Table 3

the mill in Malmö during one year was calculated (see 'Mix' column in Table 5). The CF range was considerably lower for the mix than for one single farm since the CF value was then an average for a number of farms and the extreme values were cancelled out by each other. The uncertainty in the mix CF decreased with number of farms included. When comparing the scenarios with basic and advanced traceability, the same pattern as for one farm was found; the uncertainty in the wheat mix CF increased to a lesser extent (between 6% and 19%) when soil N_2O emission uncertainty was included and considerably (between 43% and 130%) when it was excluded.

Variations between years were partly explained by seasonal variations since these gave very different moisture contents at harvest, which affected the amount of energy required to dry the wheat. The average moisture content in 2001 was 19.6% compared with 14.6% in 2003.

For part 2 (production of pasta from wheat, packaging and distribution), the emissions varied between 0.13 and 0.15 kg CO_2e/kg pasta due to measuring uncertainty in the energy spent during production and transport and uncertainty in the emissions caused by the energy carriers (electricity, natural gas, biofuel and distinct heating).

3.3 Comparison between scenarios

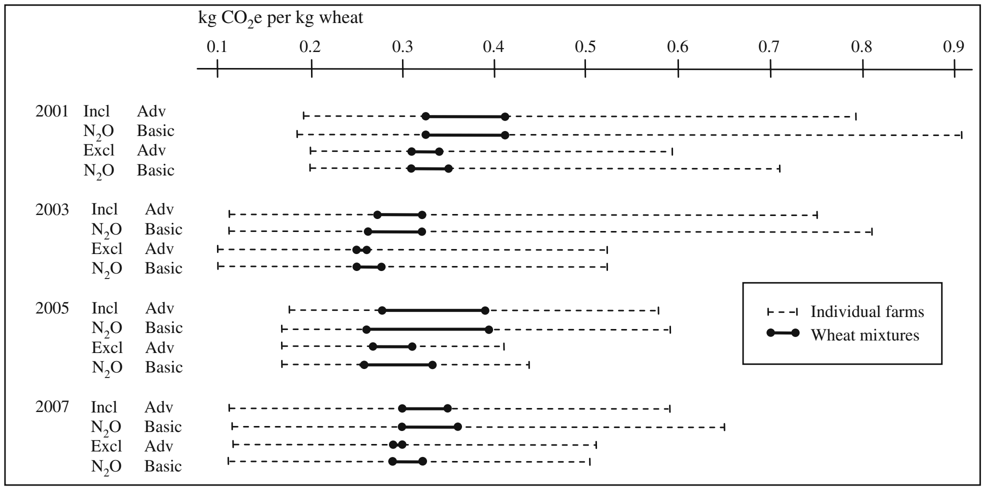
Mean wheat CF values were calculated for all farms using mean values for all parameters, except yield, amount of

Table 5 Wheat CFs for different scenarios (kilograms CO_2e per kilogram wheat before the milling process)

Scenarios		Including N_2O uncertainty				Excluding N_2O uncertainty			
		Boundaries		Range		Boundaries		Range	
		Farms	Mix	Farms	Mix	Farms	Mix	Farms	Mix
1:a	One farm, advanced traceability	0.22–0.56	–	0.34	–	0.26–0.37	–	0.11	–
1:b	One farm, basic traceability	0.22–0.57	–	0.35	–	0.26–0.41	–	0.15	–
2:a	Several farms, advanced traceability								
	2001 (51 farms)	0.19–0.79	0.32–0.41	0.60	0.09	0.20–0.59	0.31–0.34	0.39	0.03
	2003 (90 farms)	0.12–0.75	0.27–0.32	0.63	0.05	0.10–0.52	0.25–0.26	0.42	0.02
	2005 (19 farms)	0.18–0.58	0.28–0.39	0.40	0.11	0.17–0.41	0.27–0.31	0.24	0.04
	2007 (159 farms)	0.12–0.59	0.30–0.35	0.47	0.05	0.14–0.51	0.29–0.30	0.37	0.02
2:b	Several farms, basic traceability								
	2001 (51 farms)	0.18–0.91	0.32–0.41	0.73	0.09	0.20–0.71	0.31–0.35	0.51	0.04
	2003 (90 farms)	0.12–0.81	0.26–0.32	0.69	0.06	0.10–0.52	0.25–0.28	0.42	0.03
	2005 (19 farms)	0.17–0.59	0.26–0.39	0.42	0.13	0.17–0.44	0.26–0.34	0.27	0.08
	2007 (159 farms)	0.13–0.65	0.30–0.36	0.52	0.06	0.12–0.50	0.29–0.32	0.38	0.03

Boundaries are the 2.5 and 97.5 percentiles and range is the difference between the boundaries. Values in the 'Farms' column are CF values for individual farms; values in the 'Mix' column are CF values for the wheat mixture used in KGI production during the specific year

Fig. 2 Graphical illustration of wheat CFs for different scenarios (values in Table 5). '*Adv*' is advanced traceability (all farm-level primary data collected at the farm) and '*Basic*' is basic traceability (only yield, amount and type of N and municipality collected from the farms)



fertilisers and regional soil conditions for which the specific farm values were used for each farm. The farms were sorted in ascending order by the mean wheat CF value, and the top 20% of farms were placed in a 'low-emitting group' and all farms formed the reference group. MC simulations, using basic traceability, for wheat mixes from the two groups were calculated and pairwise comparisons were made of the individual CF results from the two groups. The outcome was a distribution which described the probability of wheat mix CFs differing between the two groups. As an example, a histogram of the difference in wheat CF between the two groups for the year 2005 is shown in Fig. 3. In 81% of cases, the wheat mix CF from all farms was higher (positive numbers in the histogram) than the wheat CF from farms in the 'low-emitting group'. The confidence was high for all years and number of farms, both including and excluding uncertainty in soil N_2O emissions (Table 6).

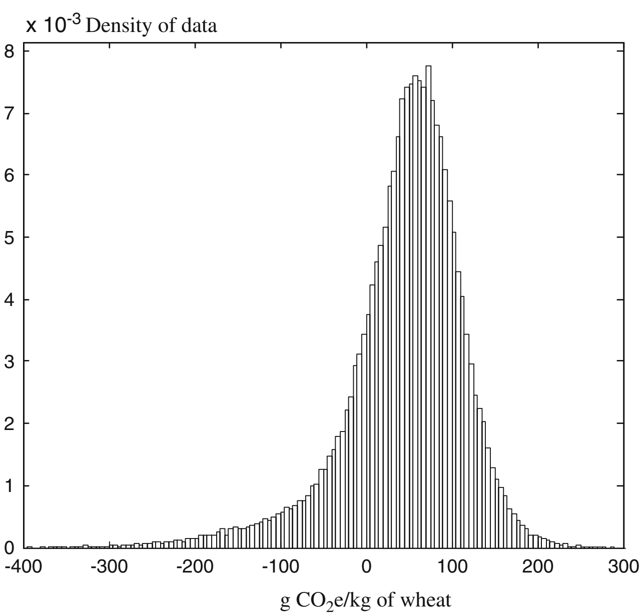


Fig. 3 Histogram of the difference in CF between wheat from all farms and 'low-emitting farms' in the year 2005 (including N_2O uncertainty)

4 Discussion

The uncertainty in soil N_2O emissions was several times larger than the uncertainty in the other GHG-emitting processes in wheat cultivation (see Fig. 1). The IPCC method used for calculating N_2O emissions assumes a linear relationship between N applied (from fertilisers and crop residuals) and emissions of N_2O from soil (IPCC 2006). This method was developed for national reporting of GHG emissions and the uncertainty distribution was chosen to represent mineral soils globally. The method does not include factors such as soil moisture content, type of crop and cropping system, fertiliser spreading technique, etc. that are known to affect the emissions of N_2O (Kasimir-Klemedtsson 2001; Rodhe et al. 2010).

It should be borne in mind that this study excluded cultivation on organic soils, which is known to drastically increase N_2O and CO_2 emissions compared with cultivation

Table 6 Probability of the wheat mix CF from farms in the 'low-emitting group' being lower than the wheat mix CF from all farms included in this study

Scenario		Probability (%)	
		Including N_2O uncertainty	Excluding N_2O uncertainty
2:b	Basic traceability		
	2001 (51 farms)	98	99.99
	2003 (90 farms)	99.99	100
	2005 (19 farms)	81	91
	2007 (159 farms)	99.99	100

on mineral soils (IPCC 2006). In a situation in which food producers competed on the basis of low GHG emissions, cultivation on organic soils could therefore never be eligible. Failure to include the 1.5% of the wheat cultivation in the Skåne region that is carried out on organic soils (Berglund et al. 2009) resulted in an underestimation of the CF values presented in this study of approximately 10%.

Yield is an important parameter in calculating wheat CF since all emissions from soil, fertiliser production and diesel combustion for field operations from an area are divided by the yield from that area in order to get the CF of 1 kg of produce. The yield depends (among other things) on the amount of N fertiliser applied, in an uncertain relationship, which further complicates the achievement of low GHG emissions. This study used real correlated values of yield and fertiliser application, which removed the uncertainty in predicted yield from a certain amount of fertiliser used. Nevertheless, due to (mainly) the uncertainty in N_2O emissions from soil, the CF of wheat from one farm and one year varied between 0.22 and 0.56 kg CO_2e/kg. It is problematic that the process that contributes the most to wheat (and pasta) CF, i.e. the emissions of N_2O from soil, is also the process associated with such overshadowing uncertainty. Serious research efforts are needed to minimise this uncertainty in order to correctly design efficient GHG reduction measures in crop production. However, due to the complexity and great variability in the process of N_2O formation in soil, producers, agricultural advisors, designers of CF systems and the LCA community will probably have to live with this uncertainty for years to come before a more precise quantification method is generally ratified. Calculating CF values for wheat (and other agricultural products) will continue to be associated with large uncertainties due to the complex relationship between yield, amount of N fertiliser and soil N_2O emissions.

When the CF of a mixture of wheat from several farms was calculated, the uncertainty in the CF decreased considerably since the wheat CF was then an average value of the CF of the wheat being delivered to the mill during that year. This also had the effect that the wheat mixture CF uncertainty decreased with the number of farms delivering wheat during a certain year. Comparing the scenarios with advanced traceability and basic traceability (only yield, amount of N and regional soil conditions) showed that with the calculation methods currently available, using data only on the yield and the amount of N applied gave a CF value that was on average only approximately 15% more uncertain than that obtained using all farm-level parameters (see Table 5). However, it could be perceived as strange to introduce a food CF calculation system that only considers yield and N, and not fossil fuel use, as reduction in fossil fuel use is often the focus when trying to cut GHG emissions. Reducing the large amounts of fossil fuels used in agriculture is of course important in climate change abatement, as well as in securing the long-term sustainability of food production. However, the uncertainty importance analysis in this study showed that the sensitivity of wheat CF to fossil fuel use (for field operations and grain drying) is low (approximately ±2%).[2] It is therefore important not to let the focus on fossil energy obscure the important task of reducing GHG emissions associated with the application of additional N in the form of mineral fertilisers, organic fertilisers, crop residues or N-fixing crops, which accelerates the release of N_2O from soil. In addition, a serious risk with focusing on maximising yields (in order to lower the CF) is the increased use of pesticides, which could lead to increased concentrations of toxic substances in water and food and, hence, threaten other environmental goals. Minimised or more efficient N usage, on the other hand, would be beneficial in decreasing eutrophication and energy use, as well as lowering the climate impact.

N_2O is also released during the production of mineral fertilisers. The process of minimising emissions of GHG from the production of mineral fertilisers is underway with the introduction of N_2O cleaning techniques in mineral fertiliser plants, which reduces the GHG emissions from production to approximately 3.6 kg CO_2e/kg N (Yara 2010) compared with the European average of 6.8 kg CO_2e/kg N used in this study (Jenssen and Kongshaug 2003). It would be beneficial for the precision in food CFs if producers of mineral fertilisers were to CF-declare their products.

As an example of differentiation between producers, a group of 'low-emitting farms' was formed by sorting the farms by their mean wheat CF values and placing the top 20% of the farms in ascending order in the 'low-emitting' group. Although yield, amount of N fertiliser and municipality (for determining regional soil conditions) were the only parameters collected from the farms, the confidence in the comparison was high. There was a range of 81–99.99% probability of the wheat mixture CF from the low-emitting farms, being less than that of a mix from all the farms (see Table 6). When individual farms were compared, the confidence was lower, but still rather good. For the year 2001, with 51 farms, the probability that the wheat CF from one farm in the low-emitting group was lower than that from the rest of the farms was 78%. Since dependencies between farms, e.g. same mineral fertiliser producer, similar transport modes and distances, etc. were not accounted for, the confidence in the comparison in this study was somewhat underestimated (see Table 6). If such

[2] This study did not consider the use of biofuels, which could make the type of fuel used a sensitive parameter depending on how the biofuels were produced and modelled (Cherubini 2009).

dependencies are strengthened, e.g. by standardising methods and data, the uncertainty in comparisons between different production alternatives can be reduced. Finnveden et al. (2009) describe this way of handling uncertainty as the 'social way'. By reaching consensus among stakeholders on how to calculate the CF, as is currently ongoing for example in the ISO 14067 (Carbon Footprint of Products) standardisation process, uncertainty can be reduced. However, consensus processes risk making the resulting outcome diverge from science and true cause–effect relationships, so care must be taken in interpreting and using the outcome of such processes.

The division of the farms through placing the top 20% in the 'low-emitting group' was a theoretical exercise that would not be practically implementable in a situation in which a producer of wheat-based products would only accept wheat from low-emitting producers since this division can only be done when the CF for all wheat in that year has been calculated. It would also be difficult to set up a limit in the form of kilograms CO_2e per kilogram of wheat. Yields and moisture contents vary between years due to non-controllable conditions such as weather and pest attacks, which make it difficult to decide on a limit beforehand that would make enough wheat available to producers of wheat-based products. However, in a hypothetical situation in which the wheat product producer has made a binding deal to sell products with a certain CF, only accepting wheat with a certain level of CF would be necessary.

The issues discussed above refer to primary production of the wheat. The stages of processing the wheat to pasta, packaging it and transporting it to the supermarket were associated with less data uncertainty as GHG emissions arise only from energy-related processes that are more easily measured. Non-negligible methodological issues can arise when dealing with the environmental impact from energy production (Cherubini et al. 2009; Dotzauer 2010). However, proposing reduction measures is more straightforward for energy- and transport-related processes than for the biological processes involved in crop production as it is 'only' a matter of increased energy and transport efficiency.

Returning to pasta and a case in which a producer would like to (or be forced to) CF-label products, or in some other way declare the CF of the pasta product, the results in this study showed that as long as the number of farms delivering wheat to the producer is not too small, the uncertainty from the mixture of wheat is considerably smaller than that from one individual farm. Restricting data collection from the farms to the parameters yield, amount of N fertiliser and location would only slightly increase the uncertainty compared with collecting data on all farm-level parameters. However, implementing a system for collecting data on only these few parameters would still require considerable amounts of effort and should only be done for a good reason. If several pasta producers from the same region were to compete based on CF values, data collection down to farm level would be necessary to differentiate between producers. If the CF were to be used for comparisons with pasta from producers in other regions or countries, it is debatable whether cultivation data based on statistics for that region could provide the necessary precision. If the perspective is broadened, and comparisons between comparable and exchangeable carbohydrate-rich products are considered, the pasta CF range for 2007, 0.45–0.52 kg CO_2e/kg KGI (steps 1 and 2), could be compared for example with that of King Edward potatoes from the Östergötland region, which had a range of 0.10–0.16 kg CO_2e/kg potatoes for the same year (Röös et al. 2010). Based on this information, one is tempted to conclude with some certainty that potatoes are a more climate-friendly alternative than KGI pasta. However, these values (like many CFs for food) only include emissions up to the supermarket and do not include preparation and the fraction of the food product that can actually be used. Potatoes are often peeled and exposed to storage damage, leading to a rather large fraction being wasted in the household (Mattsson et al. 2001), whereas pasta is associated with very small losses. The energy needed for preparing the pasta or potatoes in the household can differ considerably and depends on the method of preparation (Carlsson-Kanyama and Boström-Carlsson 2001). In addition, portion sizes for pasta are smaller since potatoes contain more water. All these factors make the choice much more difficult and illustrate the complexity in comparing CFs of different food products.

5 Conclusions

With currently available data collection and GHG emission calculation methods, the CF of wheat from one farm could not be determined more accurately than being in a range of 0.22–0.56 kg CO_2e/kg wheat, even though all farm-level primary data were collected. When data collection was restricted to the parameters yield, amount and type of N fertiliser and municipality (for determining soil humus content), which proved to be the most influential parameters, the range was only slightly increased due to the large uncertainty in the emissions of N_2O from soil. When wheat from several farms was mixed during a year, the wheat mixture CF varied approximately ±10–20% from the mean with 95% certainty. Variation in the wheat CF from individual

farms during one year was much larger. The variation in the uncertainty range was greater between years, due to different numbers of farms included in the different years, than between collecting all farm-level primary data or only the most influential parameters. More precise methods for assessing the soil N_2O emissions are needed to decrease the uncertainty significantly.

6 Recommendations and perspectives

Based on the uncertainty information determined in this study, the CF value of 1 kg of KGI should read 0.5 kg CO_2e rather than 0.50 kg CO_2e or, even better, 0.4–0.6 kg CO_2e. If the information is used for package labelling, the difference between 0.5 and 0.50 would probably not be noted by the average consumer, whilst a range might be too confusing. However, it is important not to give a false sense of accuracy. Numerical food product labelling has several other problems that are just as important as the accuracy in the numbers presented, and it will probably be difficult, at least initially, for consumers to make the right choices based on these labels (Röös and Tjärnemo 2011). The most important purpose that a numerical on-product label will have is perhaps in educating consumers about what is large and small when it comes to GHG emissions from food. Comparing the values for pasta and potato, all well below 1 kg CO_2e/kg product, with the emissions from meat and dairy products, e.g. with those for beef ranging between 15 and 28 kg CO_2e/kg (Fogelberg Lagerberg 2008), could function as an eye-opener. In such a comparison, when the ranges are far from overlapping, the exact numbers are less important.

When it comes to differentiating between producers of the same product, the accuracy of the numerical values is more crucial. Due to the difficulties in calculating accurate values, and considering the conflict with other environmental goals, finding other ways of differentiating between producers than calculating numerical CFs might be more fruitful and fair. For example, a Swedish climate certification programme for food has established a number of certification rules specifying reduction measures that the producer has to implement in order to receive CF certification, but contains no numerical information (CCfF 2010). However, this system also has several limitations (Röös and Tjärnemo 2011; SEPA 2010) and would not be applicable for cases in which numerical information is required by legislation, etc. In such cases, there is little option for the CF and LCA practitioner but to continue using existing methods and data collection strategies. However, they can provide input on improvement, contribute to standardisation processes and help raise awareness and knowledge of the associated uncertainty in the data through studies like this one.

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